Large Scale Physical Oceanographic Context for GasEx2001

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Running Title:
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Abstract. GasEx2001 is a study of air-sea gas exchange in a region of CO_2 outgassing. The main portion of the experiment involved measurements taken by and around a drifting array of near-surface instruments during the second half of February 2001, just south of the equator in the central Pacific Ocean. Physical oceanographic conditions are described using data from the cruise and a variety of other sources to set the large-scale oceanographic context for GasEx2001. The observed equatorial currents and water property distributions are typical, including the westward velocities of the South Equatorial Current, and the signature of equatorial upwelling of cold, salty, oxygen-poor, carbon-rich waters from the Equatorial Undercurrent, critical for maintenance of carbon outgassing in the region. The warming mixed layer temperature and weakening easterly trade winds observed during GasEx2001 are characteristic of boreal spring, when the equatorial cold tongue warms up. However, the shoaling pycnocline (perhaps along with upwelling) more likely resulted from the passage of a large upwelling Kelvin wave. Meridional velocities of tropical instability waves are strong enough to displace upwelled water a few hundred km from the equator during the experiment. The instrument array appeared to remain roughly behind the crest of an instability wave. This wave probably contributed to strong westward and weak equatorward drift during the course of GasEx2001, and may also have contributed to mixed layer shoaling and upwelling.

1. Introduction

GasEx2001 is a field experiment designed to study air-sea gas exchange in a region of net carbon outgassing The main part of the experiment involved observations taken from an array of drifting near-surface instruments located in recently upwelled water just south of the equator in the central Pacific Ocean, and from the ship that followed and tended to the drifting instrument array. This portion of GasEx2001 started on February 13th 2001 at 3.00°S, 125.00°W and continued through March 1st, by which time the array had drifted to 2.30°S, 131.54°W. The local dynamics and their specific impact on mixed layer budgets relevant to air-sea exchange are discussed elsewhere [*Johnson and Sabine*, 2002]. Here a wide variety of physical oceanographic phenomena that have potential effects on mixed layer conditions and hence air-sea CO_2 flux are described here to set the experiment into a large-scale context, using data collected during the experiment and from other sources.

Large-scale oceanographic dynamics of the tropical Pacific Ocean have been well understood for some time [*Philander et al.*, 1987]. Easterly trade winds blow over the region. These trades drive westward surface flow on the equator, which piles up warm water in the west and sets up a thermocline that shoals to the east. This thermocline structure supports a zonal pressure gradient on the equator that in turn drives the Equatorial Undercurrent (EUC) eastward and upward along the thermocline. Off the equator the eastward shoaling thermocline results in an equatorward component of geostrophic flow and some westward geostrophic flow (the northern and southern branches of the South Equatorial Current (SEC)) corresponding to poleward deepening of the thermocline [*Wyrki*, 1981; *Bryden and Brady*, 1985; *Johnson and McPhaden*, 1999]. Off the equator the trade winds drive a poleward Ekman transport which overwhelms the equatorward geostrophic flow creating a surface divergence near the equator [*Poulain*, 1993; *Johnson*, 2001]. This surface divergence is fed by equatorial upwelling, which is in turn fed in part by zonal convergence of the EUC and in part by meridional geostrophic convergence on the equator [*Weisberg and Qiao*, 2000; *Johnson et al.*, 2001]. The upwelled water is cold, and has a direct feedback on the atmosphere from seasonal to interannual time scales [*Philander*, 1990]. In addition, this upwelled water is also nutrient-rich, oxygen-poor, and carbon-rich, which has a direct impact on biogeochemical [*Feely et al.*, 1999] and biological [*Chavez et al.*, 1999] aspects of climate. Outgassing of these upwelled carbon-rich waters is of specific interest here.

Some of the upwelled water flows as far poleward as the subtropics. The cycle of subduction in the subtropics, equatorward geostrophic flow, equatorial upwelling, and poleward surface flow has come to be known as the subtropical cell. However, there is also evidence, both from models [*Philander et al.*, 1987; *Lu et al.*, 1998] and observations [*Johnson*, 2001; *Johnson et al.*, 2001], that some of the upwelled water is downwelled within ±8° latitude of the equator. This downwelling is thought to be confined to the upper thermocline, and the water presumably flows rapidly back to the equator in the geostrophic convergence where it is upwelled again. This shallower, more tropical recirculation has been called the tropical cell. GasEx2001 is located within the downwelling region of the tropical cell, where recently upwelled, carbon-rich water is present.

Of course the mean circulation is unlikely to be representative of synoptic conditions in the ocean, and there are a number of factors that can alter the circulation. First, this circulation is significantly modulated on interannual time-scales, and the phase of the Southern Oscillation Index (SOI) is quite important to conditions in the region, including significantly modulating CO_2 outgassing [*Feely et al.*, 1999]. However, during GasEx2001 in February 2001, the five-month running mean SOI was near 0.5 and falling, consistent with weak La Niña conditions fading to near normal. There was likely no significant perturbation by ENSO during the experiment, so interannual variability is not discussed further.

The most regular perturbation to the mean circulation is the seasonal cycle. Normally during February the easterly trade winds decrease in the central Pacific. The thermocline shoals while the cold tongue warms and the easterly trade winds weaken [*Yu and McPhaden*, 1999]. The southern branch of the SEC and the EUC are both relatively weak but strengthening, whereas the northern branch of the SEC and the NECC are on the wane [*Donguy and Meyers*, 1996; *Johnson et al.*, 2002]. The SEC exhibits mean westward near-surface flows between 0.2 and 0.3 m s^{-1} during this period.

Remotely forced equatorial Kelvin waves are one transient perturbation on the system. Winds in the western Pacific can excite Kelvin waves, which then propagate rapidly eastward along the waveguide. Kelvin waves have a significant zonal velocity signature, and can change the depth of equatorial thermocline. These depth changes modify the properties of upwelled water on the equator, as well as modifying the upwelling rate itself. Prior to GasEx2001 a westerly wind burst in the western Pacific excited a downwelling Kelvin wave, and then the termination of that wind burst excited an upwelling Kelvin wave. GasEx2001 was conducted entirely under the influence of that upwelling Kelvin wave.

Tropical instability waves (TIWs) are another near-equatorial disturbance. They are most prevalent in the Boreal summer and autumn and during La Niña conditions, when zonal currents from which the TIWs gain energy are strong [*Baturin and Niiler*, 1997]. TIWs can be highly non-linear [*Kennan and Flament*, 2000],with strong advection, upwelling, frontogenesis [*Johnson*, 1996], and lateral mixing. They thus significantly impact heat budgets [*Swenson and Hansen*, 1999], biogeochemical property distributions such as chlorophyll [*Strutton et al.*, 2001] and presumably CO_2 distributions and air-sea exchange. In fact, since TIWs involve strong ocean velocities in an area of weak winds, they can even modulate surface stress [*Polito et al.*, 2001]. TIW velocities can be of the same magnitude as the mean zonal circulation and overwhelm the mean meridional velocities by an order of magnitude. Vertical velocities associated with TIWs also overwhelm mean values on the equator [*Weisberg and Qiao*, 2000]. Normally, TIWs are relatively weak during February, but TIWs were present during GasEx2001.

Here, we characterize large-scale oceanographic conditions surrounding GasEx2001 using a mix of available data including shipboard CTD/ADCP sections, TAO mooring data, surface drifter tracks, and satellite data. First, we discuss the large-scale ocean circulation and the situation of the experiment in terms of seasonal and interannual cycles. Then, we describe the passage of two downwelling Kelvin waves. Next, we analyze evidence for TIWs and discuss their effects. Finally, we summarize to set the context of large-scale physical oceanographic conditions under which Gasex2001 was conducted.

2. Large-scale circulation and water property distributions

The equatorial system of zonal currents and water-property distributions in which Gasex2001 was situated are revealed by three cross-equatorial CTD/ADCP sections taken within a month of the experiment, in its general vicinity. Prior to the experiment, sections were occupied along 140°W (5°S to 12°N; January 19 - 27) and along 125°W (8°S to 12°N;

February 1 - 9) on the NOAA Ship *Ka'imimoana* during routine maintenance of the TAO mooring array. A section was occupied near 135°W (2°S to 5°N; March 1 - 3) on the NOAA Ship *Ronald H. Brown* at the conclusion of GasEx2001, during the steam to Hawaii. In all cases the shipboard ADCP was run continuously, collecting data from about 17 m to over 400 m at 8 m vertical resolution in 5 minute averages, and CTD stations were occupied at least every degree of latitude from the surface to at least 500 dbar at 1 dbar vertical resolution. These data are mapped to a regular latitude-depth grid following *Johnson et al.*, [2002].

Zonal velocity fields sampled by these sections (Figure 1) reveal the major equatorial currents. Climatologically, in February at these longitudes the EUC is at mid-strength and building, the NECC is at mid-strength and weakening, the north branch of the SEC is at its weakest, and the south branch of the SEC is at its strongest within its limited range of seasonal variation [*Donguy and Meyers*, 1996; *Johnson et al.*, 2002]. In the synoptic sections a robust EUC is centered near the equator and 85 - 130 m, with maximum zonal velocities of 1.1 - 1.4 m s^{-1}. A Kelvin wave may boost the eastward velocities of the EUC sampled during the 125°W occupation, as discussed in Section 4. The SEC is draped over the EUC, with westward flow in the northern branch reaching from 3 - 5°N, and some variations in strength from section to section. While the 135°W section does not extend far enough north to sample the NECC, the 125°W and 140°W sections both sample it, although with very different strengths. This variability in SEC and NECC strength may be due to TIWs, as discussed in Section 5. Merdional velocity fields do not show the surface Ekman divergence from the equator and the subsurface geostrophic convergence onto the equator that is seen in the mean fields [*Bryden and Brady*, 1981; *Johnson et al.*, 2001], but instead reveal vigorous TIW signatures discussed in Section 5.

The water property distributions of potential temperature (Figure 2) and salinity (Figure 3) are also typical of the eastern equatorial Pacific. The mixed layer is warmer, fresher, and shallower in the north, under the high precipitation and upwelling-favorable wind stress patterns of the Intertropical Convergence Zone [*Delcroix et al.*, 1996]. Salty subsurface water approaches the equator from the south and fresh subsurface water from the north. This distribution reflects the mean geostrophic convergence that feeds the EUC, supplies equatorial upwelling, and maintains a subsurface meridional salinity front along the equator [*Tsuchiya*, 1968; *Johnson and McPhaden*, 1999]. The local subsurface salinity maximum visible in all sections near 1°S is associated with eastward advection of salty water within the EUC contrasting with westward advection of fresher water in the flanking SEC [*Lukas*, 1986]. Along 135°W, where dissolved oxygen was also measured (Figure 4), the highest subsurface dissolved oxygen values on the equator between 100 and 250 m depth are also a signature of eastward water property advection in the EUC [*Tsuchiya*, 1968]. The temperature and salinity fields all show cold and salty chimneys extending up through the mixed layer near the equator (1°N during the 125°W and 135°W sections, and 2°S during the 140°W section). These features are signatures of equatorial upwelling. In the 135°W section, the upwelling region around 1°N is relatively oxygen-poor (only 93% saturated) at the surface. The deviation of the upwelling signatures from the equator is associated with strong near-surface meridional velocities, and is likely due to TIWs, as discussed in Section 5.

3. The role of the seasonal cycle

Normally during February easterly trade winds are decreasing in the Central Pacific, the thermocline is shoaling, and the sea surface temperatures are warming [*Yu and McPhaden*, 1999] Near GasEx2001 during this season the southern branch of the SEC is normally at a peak according to a climatological analyses of both XBT [*Donguy and Meyers*, 1996] and ADCP data [*Johnson et al.*, 2002]. Surface drifter velocities [*Reverdin et al.*, 1994; *Johnson*, 2001] give similar results with zonal flows in the SEC exceeding 0.3 m s^{-1}, and also allow an estimate that the seasonal cycle of meridional surface velocity in the region (climatologically southward) is at a minimum, near -0.04 m s^{-1}. However, synoptic sections of zonal velocity (Figure 1) and meridional velocity (see Figure 8 below) show considerable variability, perhaps owing to the presence of TIWs, as discussed in Section 5.

GasEx2001 is perhaps best put into the context of the progression of the seasonal cycle using a year of TAO mooring data across the Pacific at 2ºS (Figure 5), which is the TAO array latitude closest to the experiment. Sea Surface Temperature (SST) records show that the gradual warming observed during GasEx2001 is part of the seasonal cycle, as February is the start of the season when the cold tongue in the central and eastern equatorial Pacific briefly warms [*Smith and Reynolds*, 1998]. The regional effects of the seasonal cycle are also evident in satellite SST records over the course of February 2001 (see Figure 10 below). These images reveal that the cold tongue warms significantly during that month. This warming is coupled with weakening easterly trade winds (Figure 5), also typical of the seasonal cycle during February. The weakening trades reduce surface cooling and mixing, allowing the mixed layer to warm. Finally, the thermocline, here represented by the 20ºC isotherm depth (Figure 5), is generally shallower in the central Pacific during the boreal spring. However, this last aspect of the seasonal cycle is somewhat subtle, and masked by intraseasonal Kelvin wave variability, as discussed in Section 4.

4. Influence of passing Kelvin waves

Equatorial Kelvin waves were significant transients near the time and location of GasEx2001. A downwelling Kelvin wave was excited remotely by a westerly wind burst in the western equatorial Pacific (extending to 156ºE) at the end of Novermber 2000 (Figure 6). This feature was followed closely by an upwelling Kelvin wave resulting from the cessation of the westerly wind burst. One signature of this wave pair is the transient propagating depression of the equatorial thermocline, visible in positive anomalies of the 20ºC isotherm depth on the equator (Figure 6). This disturbance crossed the basin with an eastward phase velocity of around 1.9 m s^{-1}, reaching 125ºW by the end of January. The Kelvin wave transient may also account for the rather high 1.4 m s^{-1} EUC velocities observed in the ADCP data from the 125ºW section crossing the equator around 4 February (Figure 1).

With the passage of the upwelling Kelvin wave, the equatorial thermocline steadily shoaled at 125ºW during the entire month of February (Figure 6), the time period of GasEx2001. In the equatorial eastern and central Pacific the equatorial Rossby radius of deformation is around 240 km [*Chelton et al.*, 1998], which means that equatorial Kelvin wave thermocline perturbations, which have a meridional Gaussian decay scaled by twice this radius, will have a significant expression at the GasEx2001 location, which is no more than 330 km from the equator. The rate of 20ºC isotherm shoaling at the 2ºS, 125ºW TAO mooring (35 m over the 28 days of February 2001) is indicative of upwelling on the order of 1.4×10^{-5} m s^{-1} during the experiment, a value comparable to mean equatorial rates [*Weisberg* *and Qiao*, 2000]. However, a vertical migration of isopycnals or isotherms alone implies little about the diapycnal processes important for moving carbon rich waters into the mixed layer. Since the array was drifting westward into a region of deepening thermocline at the same time as the shoaling was occurring (Figure 5), these two tendencies canceled somewhat during GasEx2001.

5. Evidence for and relation to tropical instability waves

TIWs are non-linear phenomena [*Kennan and Flament*, 2000] with roughly (within factors of two) a 30 day period, a 1000 km zonal wavelength, and westward phase propagation of about 0.4 m s^{-1} [*Polito et al.*, 2001]. TIWs extract their energy from the equatorial current system [*Proehl*, 1998], and are more prevalent when these currents are strong. February is a transition time between the boreal spring, when the NECC and north SEC are weak along with the TIWs, and the rest of the year when these currents and the TIWs are strong. TIWs also strengthen with the equatorial currents during La Niña conditions [*Baturin and Niiler*, 1997]. TIW signatures are evident in SST and Sea-Surface Height (SSH) at 5°N and 2°S [*Chelton et al.*, 2001], as well as in velocity near the equator [*Qiao and Weisberg*, 1995].

In the TAO mooring data, the TIWs have strongest dynamic height signatures in the central Pacific at 5°N, with another weaker maximum south of the equator. Again, 20°C isotherm depths from TAO mooring data reveal TIW evolution around GasEx2001 (Figure 7), where TIWs are obvious as monthly oscillations in the fall of 2000 when the isotherms are deep at 5°N, indicating a strong trough in the thermocline between the north branch of the SEC and the NECC. As the trough begins to shoal (and the currents weaken) early in 2001, the TIW oscillations apparently weaken too. However, other data provide strong evidence that TIWs were still active during GasEx2001.

First, zonal velocities associated with the NECC and SEC are much stronger at 140°W than at 125°W (Figure 1), and the thermocline trough much deeper (Figure 2), despite the relatively short zonal and temporal separation of these two sections. These differences suggest strong variability over relatively short scales. Second, meridional velocities (Figure 8) in the upper ocean do not resemble the mean pattern of order 10 cm s^{-1} near-surface Ekman flow away from the equator with weaker geostrophic flow converging on the equator below [*Johnson et al.*, 2001]. In particular, the 135°W section has a strong northward flow near the equator, whereas the 140°W section has a strong southward flow. Interestingly, the water property distributions indicative of upwelling: cold (Figure 2), salty (Figure 3), and oxygen-poor (Figure 4) chimneys extending up into the mixed layer, are displaced north in the 135°W section and south in the 140°W section, in exactly the sense expected if meridional velocities, likely associated with TIWs, were to advect them off the equator.

Three drifting WOCE/TOGA buoys [*Hansen and Poulain*, 1996] that were in the general vicinity of GasEx2001 (Figure 9) in the first quarter of 2001 exhibited trajectories with cusped meridional excursions with a zonal wavelength of over 1500 km and a monthly period as they drifted westward along about 5°S. This behavior is typical of surface drifters in TIWs [*Kennan and Flament*, 2000]. In fact, the buoy closest to GasEx2001, located about 370 km SSE at the start of the experiment, drifted westward and equatorward during the time that the array drifted in those directions. This synchronicity suggests the nearby drifter and the array were sampling a similar TIW phase. However, this drifter moved more slowly than the array. This difference is speed was probably due partly to the initial separation of about 370 km between the array and the drifter, and partly to the higher windage of the array, which may have been blown westward by the easterly trades.

Finally, TIW signatures are clear in maps of microwave satellite SST data in the region (Figure 10). The zonal wavelength appears to be about 1500 km, and westward phase propagation is evident. The TIWs periodically displace the SST minimum from the equator. The GasEx2001 array drifts along behind the crest of a TIW. Observations and ocean general circulation model simulations suggest that location in this phase of the TIW is likely to be associated with strong westward velocities, little meridional velocity, and upwelling [*Kennan and Flament*, 2000].

6. Summary

A typically complex mix of ocean phenomena influenced large-scale oceanographic conditions during GasEx2001. The experiment was conducted just south of the equator in the Central Pacific during the second half of February, 2001. The zonal system of equatorial currents was observed to be within a normal range, as might be expected given the near normal phase of ENSO for the time period. Of particular relevance, the southern branch of the SEC advected the drifting array primarily westward, as expected. Water property distributions were also fairly typical. In particular, equatorial upwelling signatures were evident in chimneys of cold, salty, oxygen-poor water extending up into the mixed layer near the equator. This upwelling supplies the carbon-rich water to the surface, making the equatorial Pacific a region of strong outgassing. The expected effects of the seasonal cycle, the weakening trade winds, shoaling thermocline, and most particularly the warming mixed layer temperatures all influenced conditions during the experiment. Most notably, this seasonal cycle resulted in significant warming of the mixed layer during GasEx2001.

More transient phenomena also influenced conditions during GasEx2001. A remotely forced downwelling Kelvin wave followed immediately by an upwelling Kelvin wave passed by the experiment location in early February. The influence of the upwelling Kelvin wave during GasEx2001 evidently overwhelmed any thermocline deepening that would be expected during the westward drift of the array. The sum of these effects likely contributed to the slowly shoaling thermocline observed during the experiment. In addition, while TIWs were weakening in strength, we present ample evidence that they were still present and influential during GasEx2001. Analysis of surface drifter and satellite SST data suggest the drifting array was following the crest of a TIW. This position could help account for the rapid westward drift of the array. In addition, TIWs are associated with strong vertical velocities, and GasEx2001 appears to have been conducted in phase of the TIW conducive to strong westward flow and off-equatorial upwelling.

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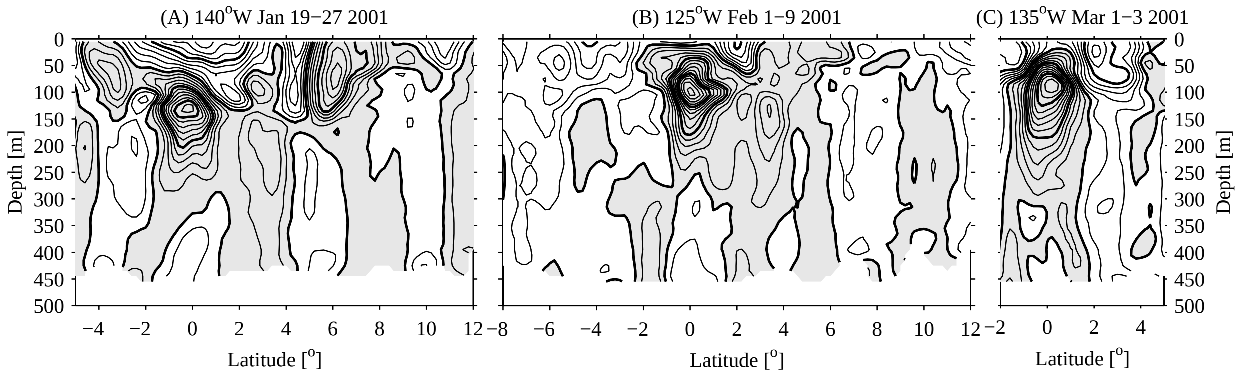

Figure 1. Vertical - meridional sections of zonal velocity from shipboard ADCP data contoured at 0.1 m s^{-1} intervals against depth [m] and latitude. Positive values are shaded and isotachs at 0.5 m s^{-1} intervals are thick. Sections were occupied (a) from 19 - 27 January 2001 nominally along 140°W on the NOAA Ship *Ka'imimoana*, (b) from 1 - 9 February 2001 nominally along 125°W on the same ship, and (c) from 1 - 3 March 2001 nominally along 135°W on the NOAA Ship *Ronald H. Brown*.

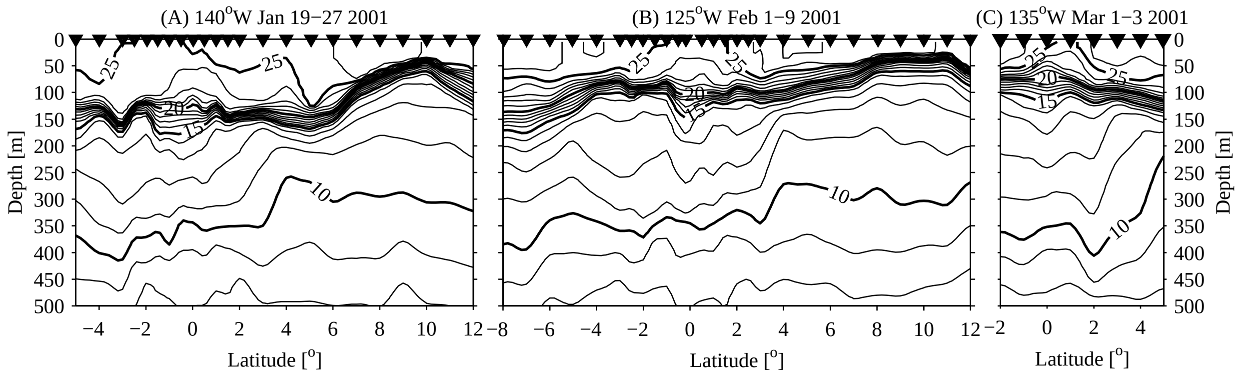

Figure 2. Vertical - meridional sections of potential temperature from CTD data contoured at 1ºC intervals against depth and latitude. Isotherms at 5ºC intervals are thick and labeled. Small triangles along upper edges show CTD station locations. Other details follow Figure 1.

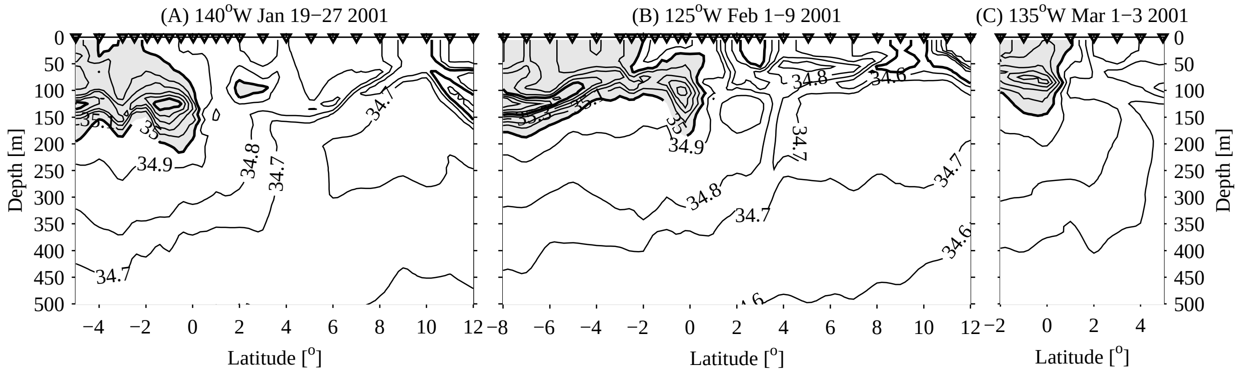

Figure 3. Vertical - meridional sections of salinity from CTD data contoured at 0.1 [PSS-78] intervals against depth and latitude. Isohalines at 0.5 intervals are thick and labeled. Values exceeding 35.0 are shaded. Other details follow Figure 2.

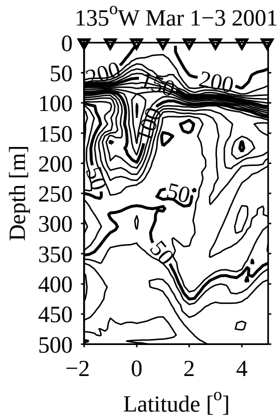

Figure 4. Vertical - meridional section of dissolved oxygen from CTD/O_2 data contoured against depth and longitude at 10 µmol kg^{-1} intervals. Oxygen isopleths at 50 µmol kg^{-1} intervals are thick and labeled. CTD oxygen was sampled only on the sections occupied from 1 - 3 March 2001 nominally along 135°W on the NOAA Ship *Ronald H. Brown*. Other details follow Figure 2.

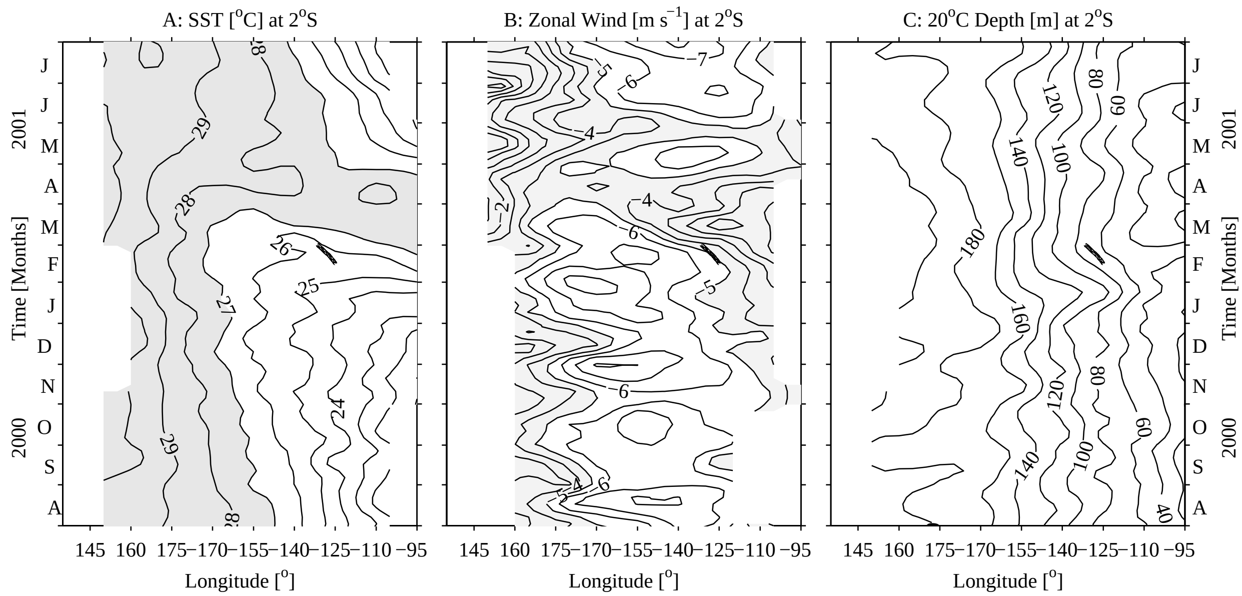

Figure 5. Time - longitude sections from TAO mooring data across the Pacific at 2^oS for a year surrounding GasEx2001 of (a) sea-surface temperature (SST) contoured at 1^oC intervals with values exceeding 27^oC shaded, (b) surface zonal wind velocity contoured at 1 m s^{-1} intervals with values exceeding -5 m s^{-1} shaded, and (c) 20^oC isotherm depth contoured at 20 m intervals. Time-longitude drift of the instrument train is denoted by a heavy solid line.

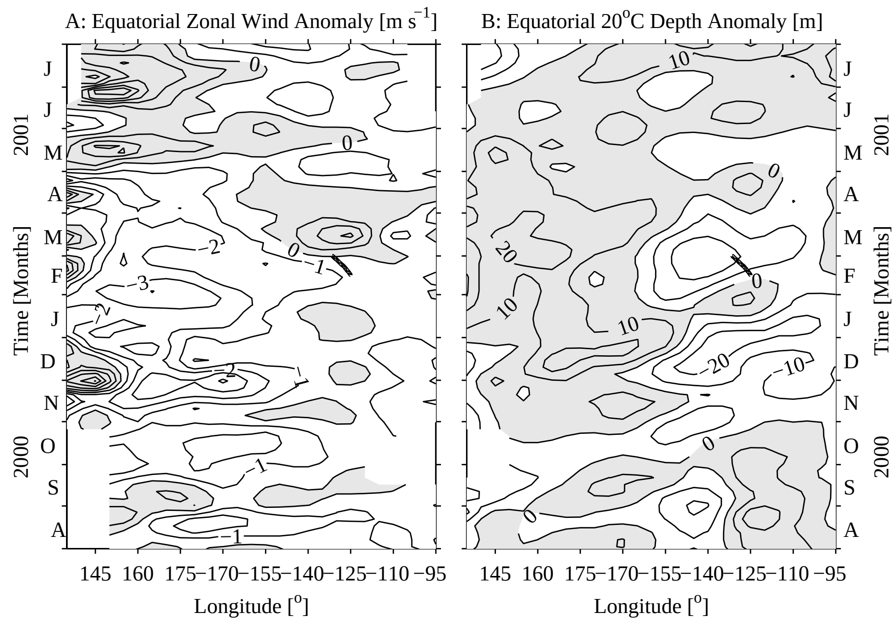

Figure 6. Time - longitude sections from TAO mooring data across the Pacific on the equator for a year surrounding GasEx2001 of (a) zonal wind speed anomaly contoured at 1 m s^{-1} intervals with positive values shaded and (b) 20^{o}C isotherm depth anomaly contoured at 10 m intervals with positive values shaded. Time-longitude drift of the instrument train is denoted by a heavy solid line.

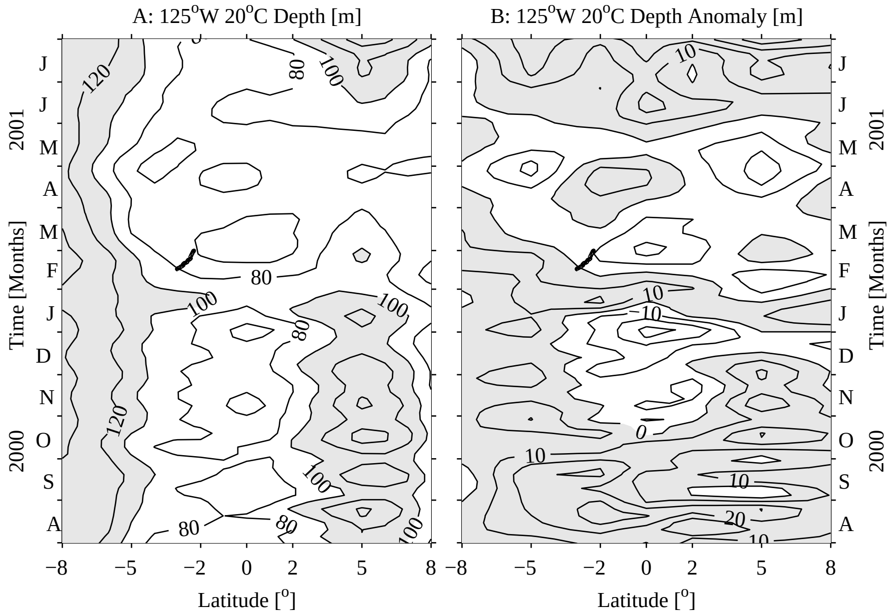

Figure 7. Time - latitude sections from TAO mooring data at 125°W for a year surrounding GasEx2001 of (a) 20°C isotherm depths contoured at 20 m intervals with depths exceeding 100 m shaded and (b) 20°C isotherm depth anomalies contoured at 10 m intervals with positive anomalies shaded. Time-latitude drift of the instrument train is denoted by a heavy solid line.

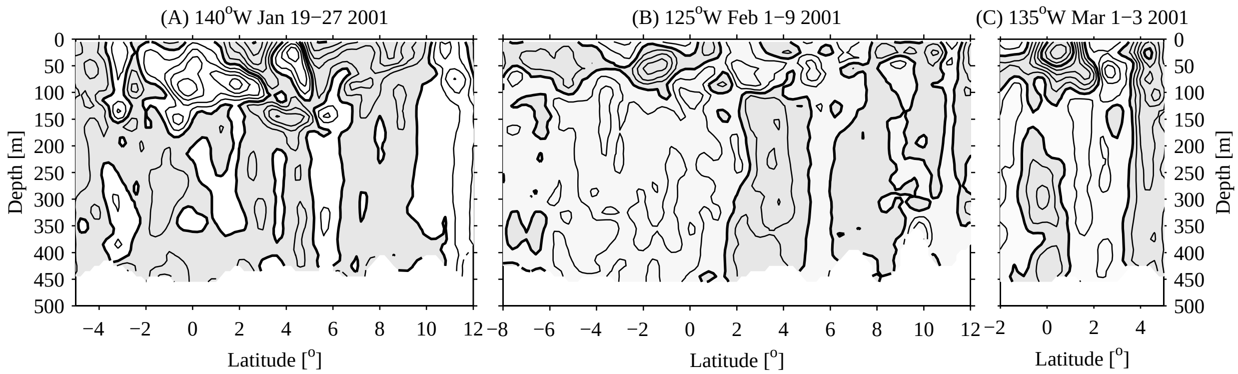

Figure 8. Vertical - meridional sections of meridional velocity from shipboard ADCP data contoured at 0.1 m s^{-1} intervals against depth [m] and latitude. Positive values are shaded and isotachs at 0.5 m s^{-1} intervals are thick. Other details follow Figure 1.

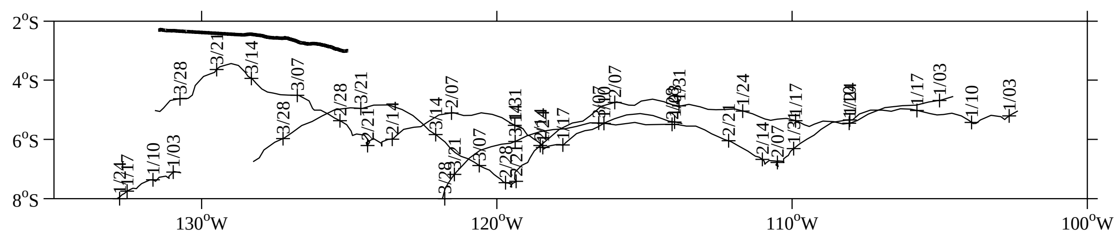

Figure 9. Daily averaged trajectories of WOCE/TOGA surface drifters located near GasEx2001 during the first three months of 2001 (encompassing the primary component period of roughly 2/14 - 3/1) with weekly position indicators (crosses with adjacent month/day notes). Drift of the instrument train is denoted by a heavy solid line.

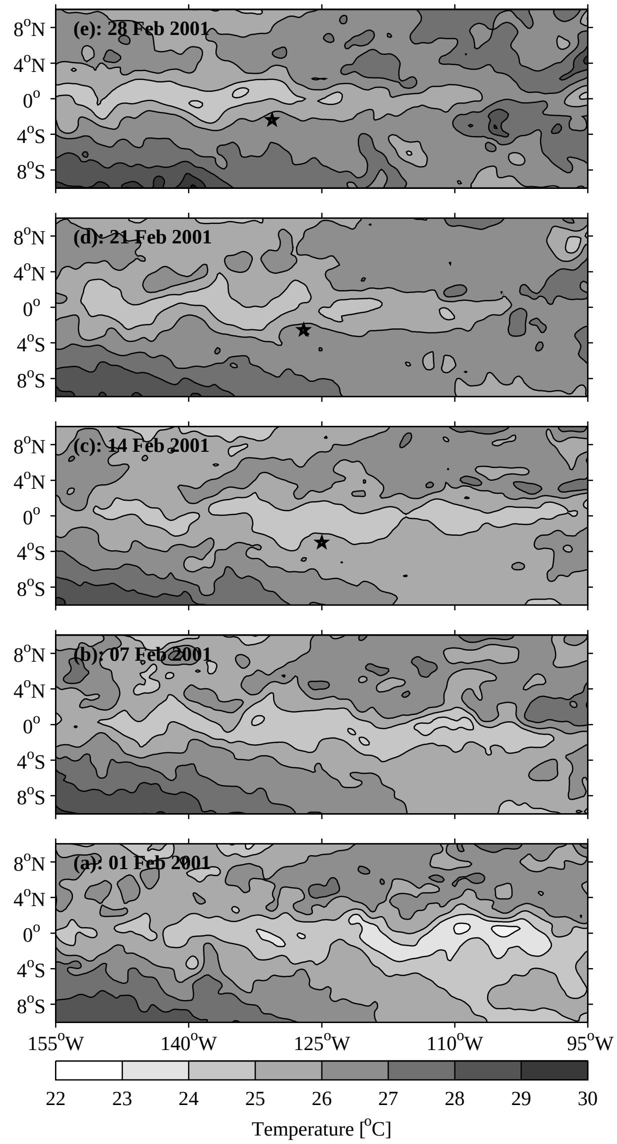

Figure 10. Weekly maps from 3-day averages of satellite microwave SST measurements spanning February 2001 in the equatorial Pacific. Data have been smoothed using a two dimensional quadratic loess smoother [*Cleveland and Devlin*, 1988] with half spans of 2° longitude and 2° latitude for purposes of presentation. Panels (a) - (e) show maps for three day periods ending on February 1st, 7th, 14th, 21st, and 28th 2001, respectively. Locations of the GasEx2001 instrument train at temporal mid-points of panels (c) - (e) are shown by pentagrams.